Part 4 Selecting Optimal Inverter Model

Chapter 7

SELECTING OPTIMAL MOTOR AND INVERTER CAPACITIES

This chapter provides you with information about the inverter output torque characteristics, selection procedure, and equations for calculating capacities to help you select optimal motor and inverter models. It also helps you select braking resistors.

Contents

7.1 Selecting Motors and Inverters

When selecting a general-purpose inverter, first select a motor and then inverter as follows:

(1) Key point for selecting a motor: Determine what kind of load machine is to be used, calculate its moment of inertia, and then select the appropriate motor capacity.

(2) Key point for selecting an inverter: Taking into account the operation requirements (e.g., acceleration time, deceleration time, and frequency in operation) of the load machine to be driven by the motor selected in (1) above, calculate the acceleration/deceleration/braking torque.

This section describes the selection procedure for (1) and (2) above. First, it explains the output torque obtained by using the motor driven by the inverter (FRENIC-Multi).

7.1.1 Motor output torque characteristics

Figures 7.1 and 7.2 graph the output torque characteristics of motors at the rated output frequency individually for 50 Hz and 60 Hz base. The horizontal and vertical axes show the output frequency and output torque (%), respectively. Curves (a) through (f) depend on the running conditions.

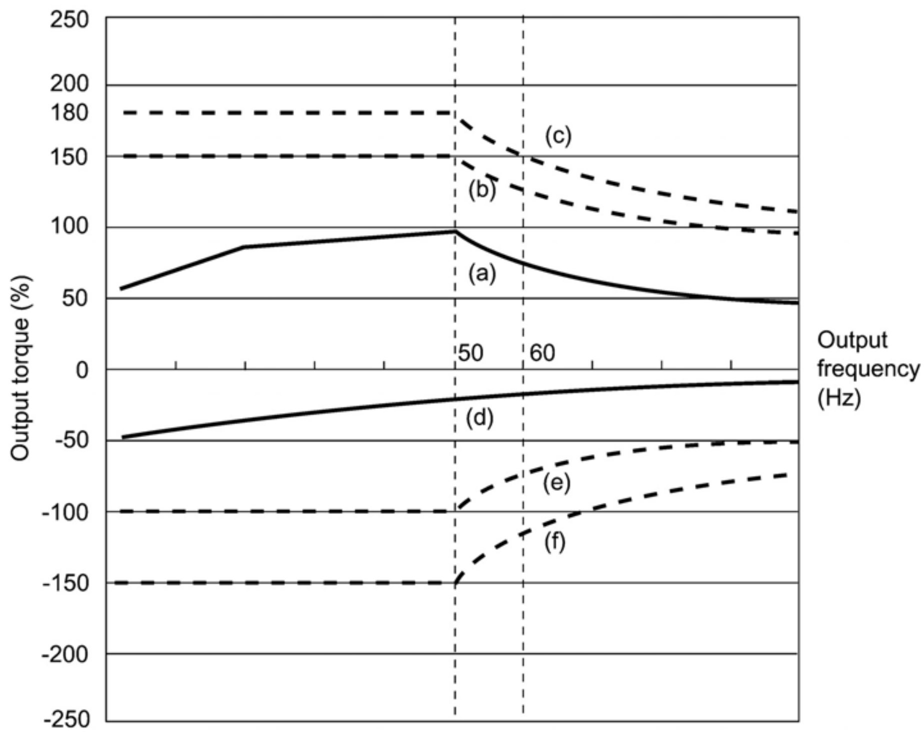

Figure 7.1 Output Torque Characteristics (Base frequency: 50 Hz)

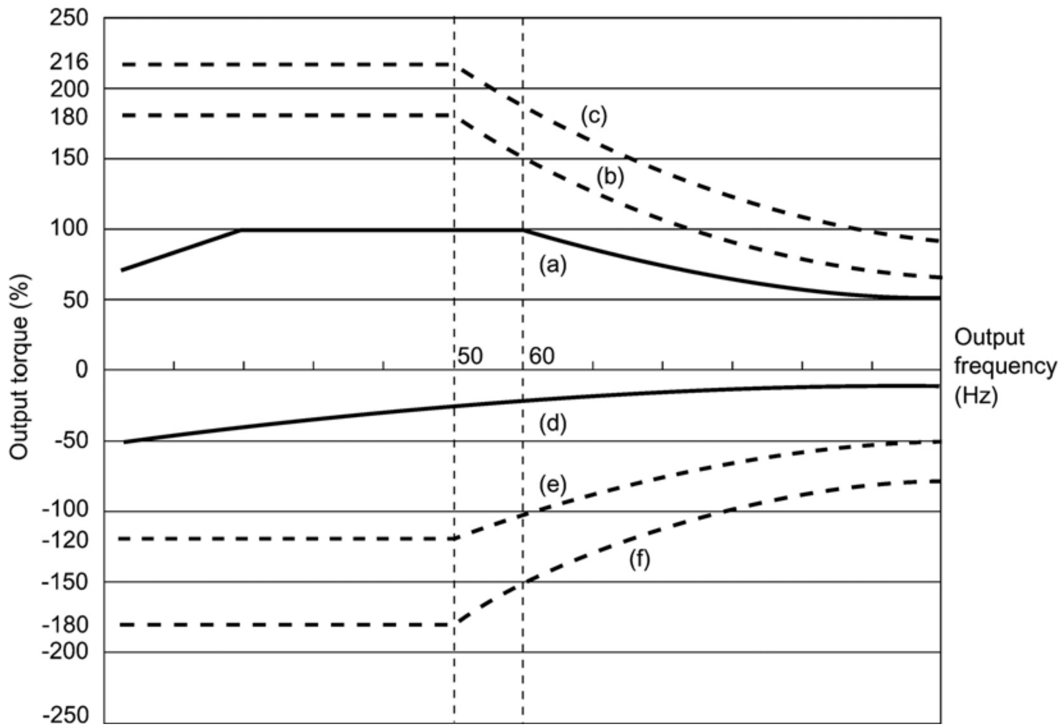

Figure 7.2 Output Torque Characteristics (Base frequency: 60 Hz)

(1) Continuous allowable driving torque (Curve (a) in Figures 7.1 and 7.2)

Curve (a) shows the torque characteristic that can be obtained in the range of the inverter continuous rated current, where the motor cooling characteristic is taken into consideration. When the motor runs at the base frequency of 60 Hz, 100 % output torque can be obtained; at 50 Hz, the output torque is somewhat lower than that in commercial power, and it further lowers at lower frequencies. The reduction of the output torque at 50 Hz is due to increased loss by inverter driving, and that at lower frequencies is mainly due to heat generation caused by the decreased ventilation performance of the motor cooling fan.

(2) Maximum driving torque in a short time (Curves (b) and (c) in Figures 7.1 and 7.2)

Curve (b) shows the torque characteristic that can be obtained in the range of the inverter rated current in a short time (the output torque is 150% for one minute) when torque-vector control is enabled. At that time, the motor cooling characteristics have little effect on the output torque.

Curve (c) shows an example of the torque characteristic when one class higher capacity inverter is used to increase the short-time maximum torque. In this case, the short-time torque is 20 to 30% greater than that when the standard capacity inverter is used.

(3) Starting torque (around the output frequency 0 Hz in Figures 7.1 and 7.2)

The maximum torque in a short time applies to the starting torque as it is.

(4) Braking torque (Curves (d), (e), and (f) in Figures 7.1 and 7.2)

In braking the motor, kinetic energy is converted to electrical energy and regenerated to the DC link bus capacitor (reservoir capacitor) of the inverter. Discharging this electrical energy to the braking resistor produces a large braking torque as shown in curve (e). If no braking resistor is provided, however, only the motor and inverter losses consume the regenerated braking energy so that the torque becomes smaller as shown in curve (d).

When an optional braking resistor is used, the braking torque is allowable only for a short time. Its time ratings are mainly determined by the braking resistor ratings. This manual and associated catalogs list the allowable values (kW) obtained from the average discharging loss and allowable values (kWs) obtained from the discharging capability that can be discharged at one time.

Note that the torque % value varies according to the inverter capacity.

Selecting an optimal brake unit enables a braking torque value to be selected comparatively freely in the range below the short-time maximum torque in the driving mode, as shown in curve (f).

For braking-related values when the inverter and braking resistor are normally combined, refer to Chapter 6, Section 6.4.1 [1] "Braking resistors."

7.1.2 Selection procedure

Figure 7.3 shows the general selection procedure for optimal inverters. Items numbered (1) through (5) are described on the following pages.

You may easily select inverter capacity if there are no restrictions on acceleration and deceleration times. If "there are any restrictions on acceleration or deceleration time" or "acceleration and deceleration are frequent," then the selection procedure is more complex.

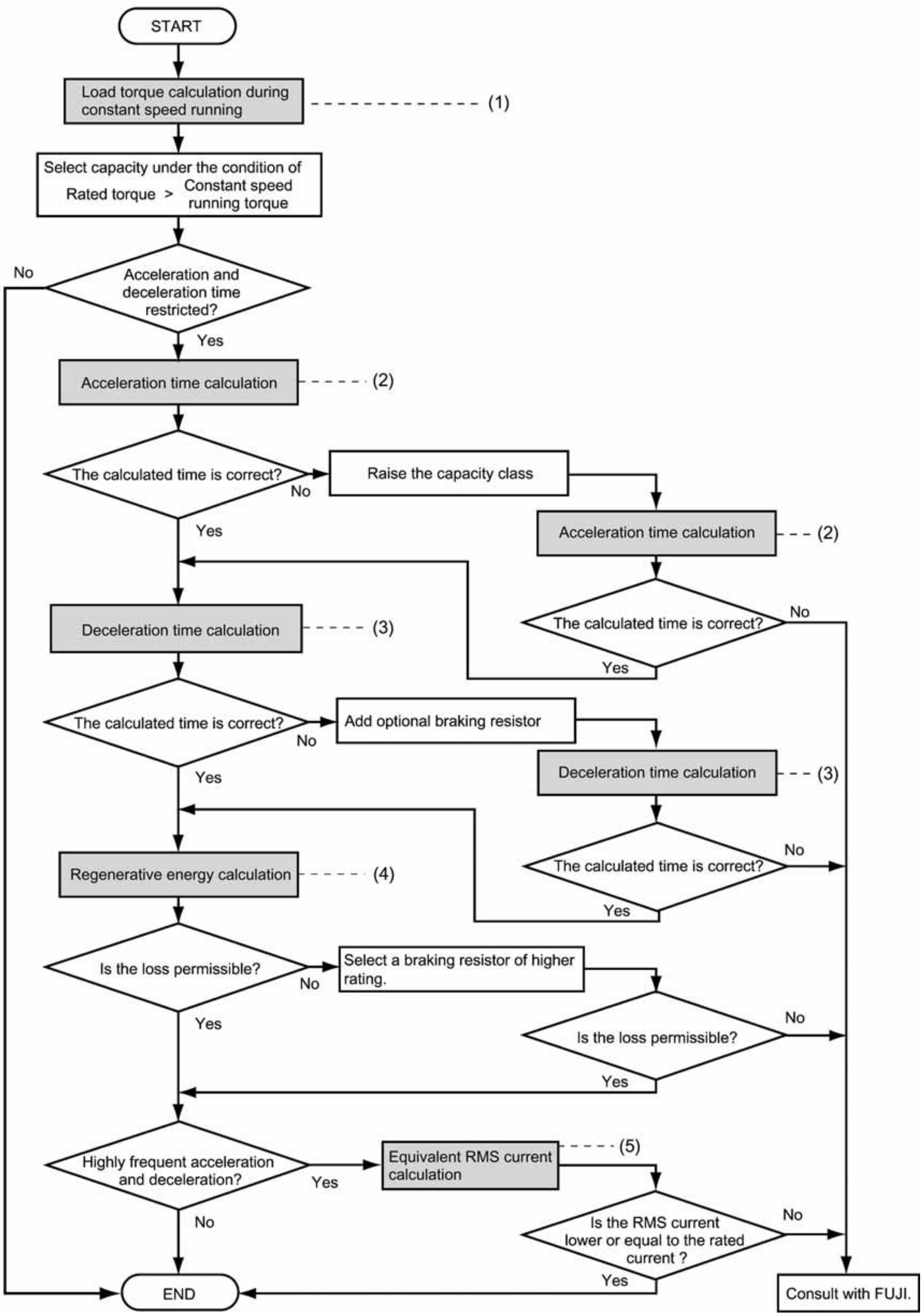

Figure 7.3 Selection Procedure

(1) Calculating the load torque during constant speed running (For detailed calculation, refer to Section 7.1.3.1)

It is essential to calculate the load torque during constant speed running for all loads.

First calculate the load torque of the motor during constant speed running and then select a tentative capacity so that the continuous rated torque of the motor during constant speed running becomes higher than the load torque. To perform capacity selection efficiently, it is necessary to match the rated speeds (base speeds) of the motor and load. To do this, select an appropriate reduction-gear (mechanical transmission) ratio and the number of motor poles.

If the acceleration or deceleration time is not restricted, the tentative capacity can apply as a defined capacity.

(2) Calculating the acceleration time (For detailed calculation, refer to Section 7.1.3.2)

When there are some specified requirements for the acceleration time, calculate it according to the following procedure:

1) Calculate the moment of inertia for the load and motor
Calculate the moment of inertia for the load, referring to Section 7.1.3.2, "Acceleration and deceleration time calculation." For the motor, refer to the related motor catalogs.

2) Calculate the minimum acceleration torque (See Figure 7.4)
The acceleration torque is the difference between the motor short-time output torque (base frequency: 60 Hz) explained in Section 7.1.1 (2), "Maximum driving torque in a short time" and the load torque (τ_L / η_G) during constant speed running calculated in the above (1). Calculate the minimum acceleration torque for the whole range of speed.

3) Calculate the acceleration time
Assign the value calculated above to the equation (7.10) in Section 7.1.3.2, "Acceleration and deceleration time calculation" to calculate the acceleration time. If the calculated acceleration time is longer than the expected time, select the inverter and motor having one class larger capacity and calculate it again.

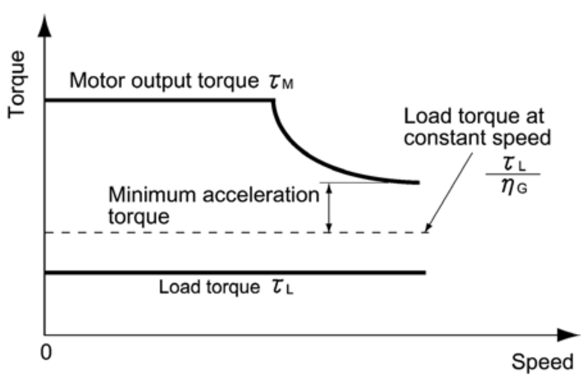

Figure 7.4 Example Study of Minimum Acceleration Torque

(3) Deceleration time (For detailed calculation, refer to Section 7.1.3.2)

To calculate the deceleration time, check the motor deceleration torque characteristics for the whole range of speed in the same way as for the acceleration time.

1) Calculate the moment of inertia for the load and motor
Same as for the acceleration time.

2) Calculate the minimum deceleration torque (See Figures 7.5 and 7.6.)
Same as for the deceleration time.

3) Calculate the deceleration time
Assign the value calculated above to the equation (7.11) to calculate the deceleration time in the same way as for the acceleration time. If the calculated deceleration time is longer than the requested time, select the inverter and motor having one class larger capacity and calculate it again.

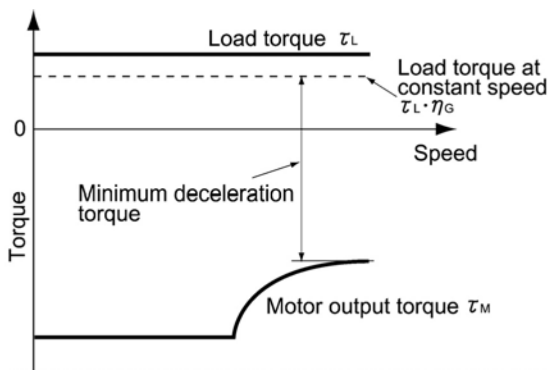

Figure 7.5 Example Study of Minimum Deceleration Torque (1)

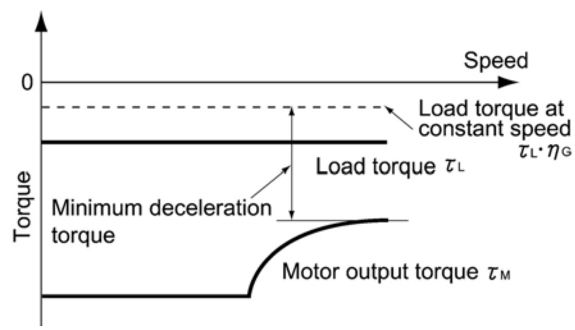

Figure 7.6 Example Study of Minimum Deceleration Torque (2)

(4) Braking resistor rating (For detailed calculation, refer to Section 7.1.3.3)

Braking resistor rating is classified into two types according to the braking periodic duty cycle.

1) When the periodic duty cycle is shorter than 100 sec:
Calculate the average loss to determine rated values.

2) When the periodic duty cycle is 100 sec or longer:
The allowable braking energy depends on the maximum regenerative braking capacity. The allowable values are listed in Chapter 6, Section 6.4.1 [1] "Braking resistors."

(5) Motor RMS current (For detailed calculation, refer to Section 7.1.3.4)

In metal processing machine and materials handling machines requiring positioning control, highly frequent running for a short time is repeated. In this case, calculate the maximum equivalent RMS current value (effective value of current) not to exceed the allowable value (rated current) for the motor.

7.1.3 Equations for selections

7.1.3.1 Load torque during constant speed running

[1] General equation

The frictional force acting on a horizontally moved load must be calculated. Calculation for driving a load along a straight line with the motor is shown below.

Where the force to move a load linearly at constant speed υ (m/s) is F (N) and the motor speed for driving this is N_M (r/min), the required motor output torque τ_M (N·m) is as follows:

$$\tau_M = \frac{60 \cdot \upsilon}{2\pi \cdot N_M} \cdot \frac{F}{\eta_G} \quad (N \cdot m) \qquad (7.1)$$

where, η_G is Reduction-gear efficiency.

When the inverter brakes the motor, efficiency works inversely, so the required motor torque should be calculated as follows:

$$\tau_M = \frac{60 \cdot \upsilon}{2\pi \cdot N_M} \cdot F \cdot \eta_G \quad (N \cdot m) \qquad (7.2)$$

$(60 \cdot \upsilon) / (2\pi \cdot N_M)$ in the above equation is an equivalent turning radius corresponding to speed υ (m/s) around the motor shaft.

The value F (N) in the above equations depends on the load type.

[2] Obtaining the required force F

Moving a load horizontally

A simplified mechanical configuration is assumed as shown in Figure 7.7. If the mass of the carrier table is W_0 (kg), the load is W (kg), and the friction coefficient of the ball screw is μ, then the friction force F (N) is expressed as follows, which is equal to a required force for driving the load:

$$F = (W_0 + W) \cdot g \cdot \mu \quad (N) \qquad (7.3)$$

where, g is the gravity acceleration ($\approx$ 9.8 (m/s^2)).

Then, the driving torque around the motor shaft is expressed as follows:

$$\tau_M = \frac{60 \cdot \upsilon}{2\pi \cdot N_M} \cdot \frac{(W_0 + W) \cdot g \cdot \mu}{\eta_G} \quad (N \cdot m) \qquad (7.4)$$

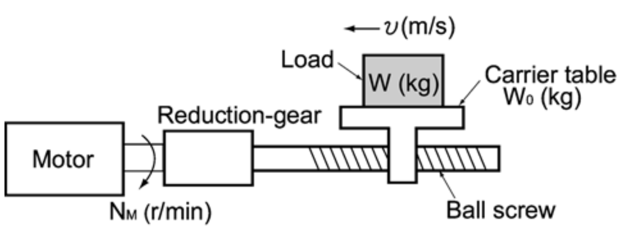

Figure 7.7 Moving a Load Horizontally

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7.1.3.2 Acceleration and deceleration time calculation

When an object whose moment of inertia is J ($kg \cdot m^2$) rotates at the speed N (r/min), it has the following kinetic energy:

$$E = \frac{J}{2} \bullet \left(\frac{2\pi \bullet N}{60}\right)^2 \quad (J) \qquad (7.5)$$

To accelerate the above rotational object, the kinetic energy will be increased; to decelerate the object, the kinetic energy must be discharged. The torque required for acceleration and deceleration can be expressed as follows:

$$\tau = J \bullet \frac{2\pi}{60} \left(\frac{dN}{dt}\right) \quad (N \bullet m) \qquad (7.6)$$

This way, the mechanical moment of inertia is an important element in the acceleration and deceleration. First, calculation method of moment of inertia is described, then those for acceleration and deceleration time are explained.

[1] Calculation of moment of inertia

For an object that rotates around the shaft, virtually divide the object into small segments and square the distance from the shaft to each segment. Then, sum the squares of the distances and the masses of the segments to calculate the moment of inertia.

$$J = \sum (W_i \bullet r_i^2) \quad (kg \bullet m^2) \qquad (7.7)$$

The following describes equations to calculate moment of inertia having different shaped loads or load systems.

(1) Hollow cylinder and solid cylinder

The common shape of a rotating body is hollow cylinder. The moment of inertia J ($kg \cdot m^2$) around the hollow cylinder center axis can be calculated as follows, where the outer and inner diameters are D_1 and D_2 [m] and total mass is W [kg] in Figure 7.8.

$$J = \frac{W \bullet (D_1^2 + D_2^2)}{8} \quad (kg \bullet m^2) \qquad (7.8)$$

For a similar shape, a solid cylinder, calculate the moment of inertia as D_2 is 0.

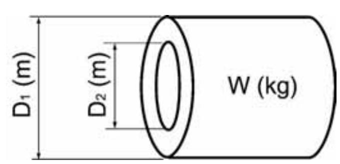
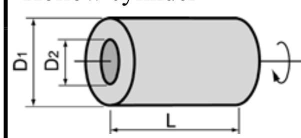
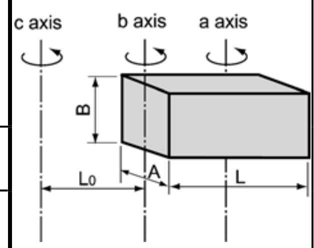
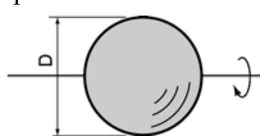
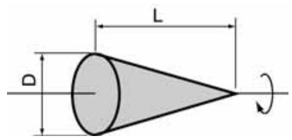
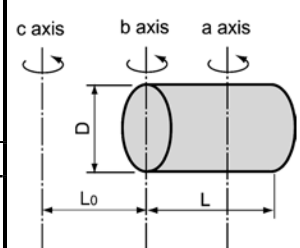
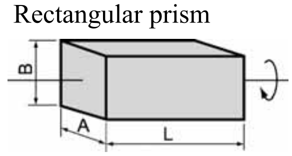
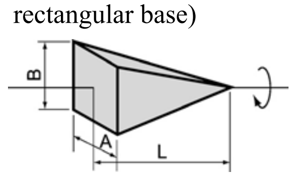
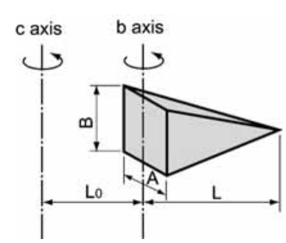
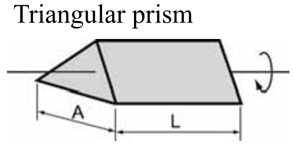
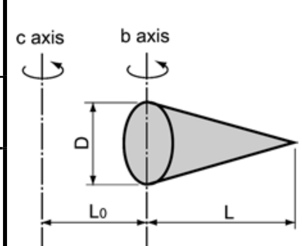
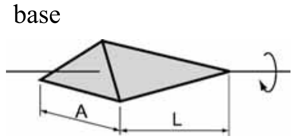


Figure 7.8 Hollow Cylinder

(2) For a general rotating body

Table 7.1 lists the calculation equations of moment of inertia of various rotating bodies including the above cylindrical rotating body.

Table 7.1 Moment of Inertia of Various Rotating Bodies

Shape	Mass: W (kg) Moment of inertia: J ($kg \cdot m^2$)	Shape	Mass: W (kg) Moment of inertia: J ($kg \cdot m^2$)
Hollow cylinder 	$W = \frac{\pi}{4} \cdot (D_1^2 - D_2^2) \cdot L \cdot \rho$ $J = \frac{1}{8} \cdot W \cdot (D_1^2 + D_2^2)$		$W = A \cdot B \cdot L \cdot \rho$ $J_a = \frac{1}{12} \cdot W \cdot (L^2 + A^2)$ $J_b = \frac{1}{12} \cdot W \cdot (L^2 + \frac{1}{4} \cdot A^2)$ $J_c \approx W \cdot (L_0^2 + L_0 \cdot L + \frac{1}{3} \cdot L^2)$
Sphere 	$W = \frac{\pi}{6} \cdot D^3 \cdot \rho$ $J = \frac{1}{10} \cdot W \cdot D^2$		
Cone 	$W = \frac{\pi}{12} \cdot D^2 \cdot L \cdot \rho$ $J = \frac{3}{40} \cdot W \cdot D^2$		$W = \frac{\pi}{4} \cdot D^2 \cdot L \cdot \rho$ $J_a = \frac{1}{12} \cdot W \cdot (L^2 + \frac{3}{4} \cdot D^2)$ $J_b = \frac{1}{3} \cdot W \cdot (L^2 + \frac{3}{16} \cdot D^2)$ $J_c \approx W \cdot (L_0^2 + L_0 \cdot L + \frac{1}{3} \cdot L^2)$
Rectangular prism 	$W = A \cdot B \cdot L \cdot \rho$ $J = \frac{1}{12} \cdot W \cdot (A^2 + B^2)$		
Square cone (Pyramid, rectangular base) 	$W = \frac{1}{3} \cdot A \cdot B \cdot L \cdot \rho$ $J = \frac{1}{20} \cdot W \cdot (A^2 + B^2)$		$W = \frac{1}{3} \cdot A \cdot B \cdot L \cdot \rho$ $J_b = \frac{1}{10} \cdot W \cdot (L^2 + \frac{1}{4} \cdot A^2)$ $J_c \approx W \cdot (L_0^2 + \frac{3}{2} \cdot L_0 \cdot L + \frac{3}{5} \cdot L^2)$
Triangular prism 	$W = \frac{\sqrt{3}}{4} \cdot A^2 \cdot L \cdot \rho$ $J = \frac{1}{3} \cdot W \cdot A^2$		$W = \frac{\pi}{12} \cdot D^2 \cdot L \cdot \rho$ $J_b = \frac{1}{10} \cdot W \cdot (L^2 + \frac{3}{8} \cdot D^2)$ $J_c \approx W \cdot (L_0^2 + \frac{3}{2} \cdot L_0 \cdot L + \frac{3}{5} \cdot L^2)$
Tetrahedron with an equilateral triangular base 	$W = \frac{\sqrt{3}}{12} \cdot A^2 \cdot L \cdot \rho$ $J = \frac{1}{5} \cdot W \cdot A^2$		
Main metal density (at 20°C) $\rho (kg/m^3)$ Iron: 7860, Copper: 8940, Aluminum: 2700			

(3) For a load running horizontally

Assume a carrier table driven by a motor as shown in Figure 7.7. If the table speed is υ (m/s) when the motor speed is N_M (r/min), then an equivalent distance from the shaft is equal to $60 \cdot \upsilon / (2\pi \cdot N_M)$ (m). The moment of inertia of the table and load to the shaft is calculated as follows:

$$J = \left(\frac{60 \cdot \upsilon}{2\pi \cdot N_M}\right)^2 \cdot (W_0 + W) \quad (kg \cdot m^2) \tag{7.9}$$

[2] Calculation of the acceleration time

Figure 7.9 shows a general load model. Assume that a motor drives a load via a reduction-gear with efficiency η_G. The time required to accelerate this load in stop state to a speed of N_M (r/min) is calculated with the following equation:

$$t_{ACC} = \frac{J_1 + J_2/\eta_G}{\tau_M - \tau_L/\eta_G} \cdot \frac{2\pi \cdot (N_M - 0)}{60} \quad (s) \tag{7.10}$$

where,

J_1: Motor shaft moment of inertia (kg·m^2)
J_2: Load shaft moment of inertia converted to motor shaft (kg·m^2)
τ_M: Minimum motor output torque in driving motor (N·m)
τ_L: Maximum load torque converted to motor shaft (N·m)
η_G: Reduction-gear efficiency.

As clarified in the above equation, the equivalent moment of inertia becomes (J_1+J_2/η_G) by considering the reduction-gear efficiency.

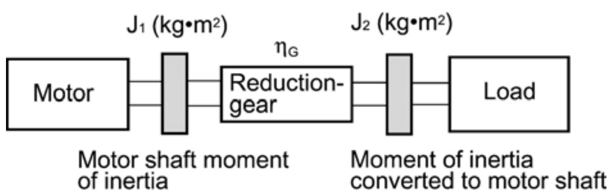


Figure 7.9 Load Model Including Reduction-gear

[3] Calculation of the deceleration time

In a load system shown in Figure 7.9, the time needed to stop the motor rotating at a speed of N_M (r/min) is calculated with the following equation:

$$t_{DEC} = \frac{J_1 + J_2 \cdot \eta_G}{\tau_M - \tau_L \cdot \eta_G} \cdot \frac{2\pi \cdot (0 - N_M)}{60} \quad (s) \tag{7.11}$$

where,

J_1: Motor shaft moment of inertia (kg·m^2)
J_2: Load shaft moment of inertia converted to motor shaft (kg·m^2)
τ_M: Minimum motor output torque in braking (or decelerating) motor (N·m)
τ_L: Maximum load torque converted to motor shaft (N·m)
η_G: Reduction-gear efficiency

In the above equation, generally output torque τ_M is negative and load torque τ_L is positive. So, deceleration time becomes shorter.

7.1.3.3 Heat energy calculation of braking resistor

If the inverter brakes the motor, the kinetic energy of mechanical load is converted to electric energy to be regenerated into the inverter circuit. This regenerative energy is often consumed in so-called braking resistors as heat. The following explains the braking resistor rating.

[1] Calculation of regenerative energy

In the inverter operation, one of the regenerative energy sources is the kinetic energy that is generated at the time an object is moved by an inertial force.

Kinetic energy of a moving object

When an object with moment of inertia J (kg·m^2) rotates at a speed N_2 (r/min), its kinetic energy is as follows:

$$E = \frac{J}{2} \bullet \left(\frac{2\pi \bullet N_2}{60}\right)^2 \quad (J) \qquad (7.12)$$

$$\approx \frac{1}{182.4} \bullet J \bullet N_2^2 \quad (J) \qquad (7.12)'$$

When this object is decelerated to a speed N_1 (r/min), the output energy is as follows:

$$E = \frac{J}{2} \bullet \left[\left(\frac{2\pi \bullet N_2}{60}\right)^2 - \left(\frac{2\pi \bullet N_1}{60}\right)^2\right] \quad (J) \qquad (7.13)$$

$$\approx \frac{1}{182.4} \bullet J \bullet (N_2^2 - N_1^2) \quad (J) \qquad (7.13)'$$

The energy regenerated to the inverter as shown in Figure 7.9 is calculated from the reduction-gear efficiency η_G and motor efficiency τ_M as follows:

$$E \approx \frac{1}{182.4} \bullet \left(J_1 + J_2 \bullet \eta_G\right) \bullet \eta_M \bullet \left(N_2^2 - N_1^2\right) \quad (J) \qquad (7.14)$$

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7.1.3.4 Calculating the RMS rating of the motor

In case of the load which is repeatedly and very frequently driven by a motor, the motor current fluctuates largely and enters the short-time rating range of the motor repeatedly. Therefore, you have to review the allowable thermal rating of the motor. The heat value is assumed to be approximately proportional to the square of the motor current.

If an inverter drives a motor in duty cycles that are much shorter than the thermal time constant of the motor, calculate the "equivalent RMS current" as mentioned below, and select the motor so that this RMS current will not exceed the rated current of the motor.

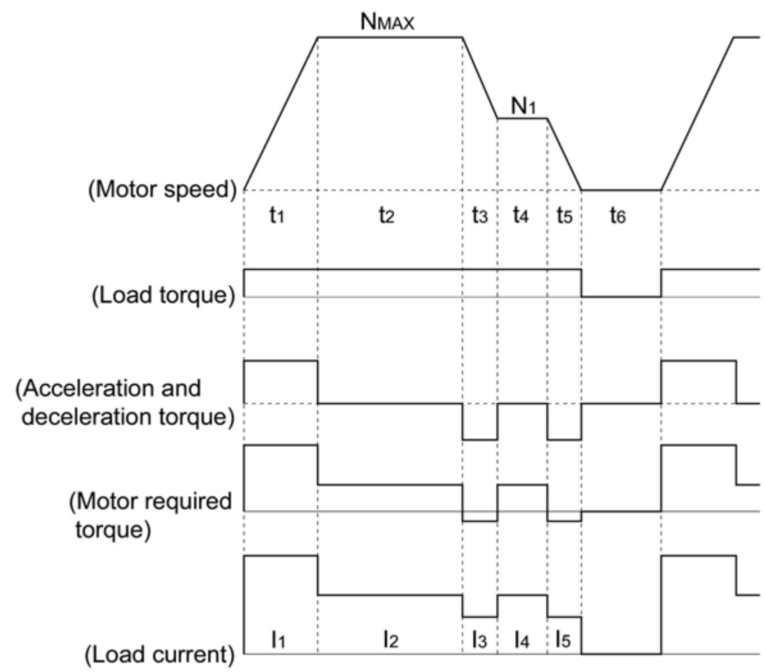

Figure 7.10 Sample of the Repetitive Operation

First, calculate the required torque of each part based on the speed pattern. Then using the torque-current curve of the motor, convert the torque to the motor current. The "equivalent RMS current, Ieq" can be finally calculated by the following equation:

$$I_{eq} = \sqrt{\frac{I_1^2 \cdot t_1 + I_2^2 \cdot t_2 + I_3^2 \cdot t_3 + I_4^2 \cdot t_4 + I_5^2 \cdot t_5}{t_1 + t_2 + t_3 + t_4 + t_5 + t_6}} \quad \text{(A)} \qquad (7.15)$$

The torque-current curve for the dedicated motor is not available for actual calculation. Therefore, calculate the motor current I from the load torque τ_1 using the following equation (7.16). Then, calculate the equivalent current I_{eq}:

$$I = \sqrt{\left(\frac{\tau_1}{100} \times I_{t100}^2\right)^2 + I_{m100}^2} \quad \text{(A)} \qquad (7.16)$$

Where, τ_1 is the load torque (%), I_{t100} is the torque current, and I_{m100} is exciting current.

7.2 Selecting a Braking Resistor

7.2.1 Selection procedure

The following three requirements must be satisfied simultaneously:

1) The maximum braking torque should not exceed values listed in Tables 6.6 to 6.8 in Chapter 6, Section 6.4.1 [1] "Braking resistors." To use the maximum braking torque exceeding values in those tables, select the braking resistor having one class larger capacity.
2) The discharge energy for a single braking action should not exceed the discharging capability (kWs) listed in Tables 6.6 to 6.8 in Chapter 6, Section 6.4.1 [1] "Braking resistors." For detailed calculation, refer to Section 7.1.3.3 "Heat energy calculation of braking resistor."
3) The average loss that is calculated by dividing the discharge energy by the cyclic period must not exceed the average loss (kW) listed in Tables 6.6 to 6.8 in Chapter 6, Section 6.4.1 [1] "Braking resistors."

7.2.2 Notes on selection

The braking time T_1, cyclic period T_0, and duty cycle %ED are converted under deceleration braking conditions based on the rated torque as shown below. However, you do not need to consider these values when selecting the braking resistor capacity.

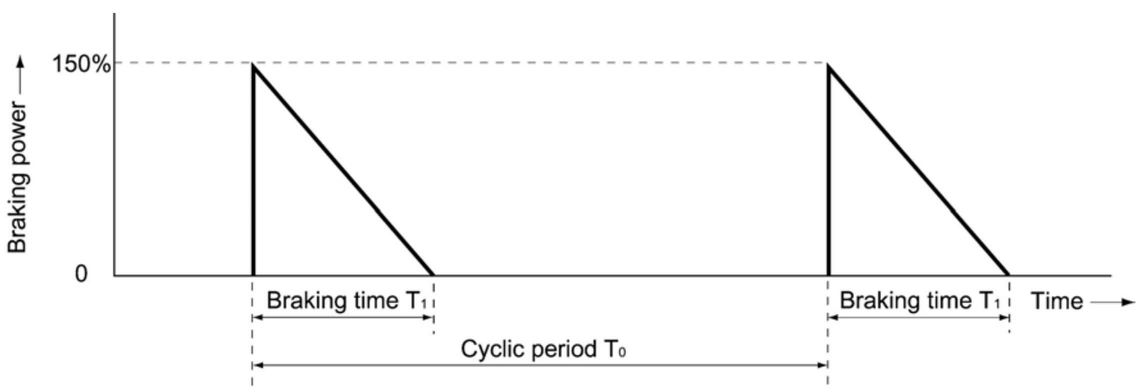

Figure 7.11 Duty Cycle